ARMY RESEARCH LABORATORY

The Ballistic and Corrosion Evaluation of Magnesium Elektron E675 vs. Baseline Magnesium Alloy AZ31B and Aluminum Alloy 5083 for Armor Applications

by Tyrone Jones and Brian Placzankis

ARL-TR-5565 **June 2011**

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Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

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Weapons and Materials Research Directorate, ARL

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13. SUPPLEMENTARY NOTES					
14. ABSTRACT The U.S. Army Research Laboratory has evaluated the ballistic and corrosion performance of high-strength magnesium alloy Elektron 675 for use in vehicle and personnel protection. The performance of Elektron 675 is compared to baseline magnesium alloy AZ31B and baseline aluminum alloy 5083 (AA5083). While Mg alloy E675 offers a higher ballistic protection at equal weight, Elektron 675 did not pass the corrosion resistance requirement specified in military specification MIL-DTL-32333. The areal density and cost will also need to be addressed for consideration as an armor material.					
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1. Introduction

The U.S. Army Research Laboratory (ARL) has been investigating the ballistic potential of magnesium (Mg) alloys for use in vehicle and personnel protection. Military specification MIL-DTL-32333 (*1*) uses commercially available Mg AZ31B alloy as the baseline for monolithic armor plate. Rolled AZ31B has been shown to be an effective substitution for aluminum (Al) alloy 5083-H131 (AA5083) against armor-piercing (AP) projectiles on an equivalent weight basis. The weight-neutral AZ31B-H24 plate would be 50% thicker than the AA5083-H131 it might replace. ARL evaluated the proprietary, high strength, Magnesium Elektron 675 (Mg E675) alloy in an effort to determine if this alloy has improved performance compared to the baseline AZ31B-H24 alloy.

2. Material Properties

The chemical composition of commercially pure melt grade magnesium (CPMg 9980B) (*2*), Mg AZ31B (*1*), and AA5083 (*3*) are provided in table 1 for comparison. The general composition of Mg E675 (*2*) is proprietary by Magnesium Elektron.

The mechanical properties and density of CPMg 9980B (*2*), Mg AZ31B (*1*), and AA5083 (*3*) are provided in table 2 and compared to Mg E675 (*2*) for comparison. Although having a higher density, the yield strength of Mg E675 is over two times the yield strength of Mg AZ31B. This is a critical property in reducing the plastic failure of the material. The ductility is marginally better than Mg AZ31B.

Table 1. Chemical composition (%) of metal alloys.

Element (%)/Alloy	**CPMg 9980B**	**AZ31B-H24**	**AA5083-H131**
Aluminum	—	2.5–3.5	REM
Manganese	0.10 max	0.2–1.0	0.40–1.0
Zinc	—	0.6–1.4	0.25 max
Yttrium	—	—	—
Neodymium	—	—	—
Rare earths (total)	—	—	—
Zirconium	—	—	—
Silicon	—	0.10 max	0.40 max
Copper	0.02 max	0.05 max	0.10 max
Nickel	0.005 max	0.005 max	—
Iron	—	0.005 max	0.40 max
Calcium	—	0.04 max	—
Chromium	—	—	0.05–0.25 max
Lead	0.01max	—	—
Tin	0.01 max	—	—
Titanium	—	—	0.15 max
Others each	0.05 max	—	0.05 max
Others total	—	0.30 max	0.15 max
Magnesium	99.80 min	REM	4.0–4.9 max
Specification cited	ASTM-B92	ASTM-B90	ASTM-B209

Table 2. Quasi-static properties of metal alloys.

Property/Alloy	**CPMg 9980B**	**Mg AZ31B-H24**	**AA5083-H131**	**Mg E675-T5**
Yield stress (MPa)	21	125	282	310
Ultimate tensile stress (MPa)	90	235	391	410
Elongation (%)	4	7	13	9
Form	Cast	Rolled	Rolled	Extruded
Density (g/cm^3)	1.74	1.77	2.66	1.95

3. Experimental Test Methodology

Ballistic testing of extruded Mg E675-T5 plates was performed by ARL at Aberdeen Proving Ground, MD, in accordance with MIL-STD-662F (*4*). Ballistic results were characterized using the standard V_{50} test methodology, also documented in MIL-STD-662F.

Magnesium Elektron provided ARL with E675 plates in the following thicknesses: 1.5, 2.5, and 3 in. These plates were evaluated against the 0.30-cal. AP M2 (figure 1), 0.50-cal. fragment simulating projectile (FSP) (figure 2), and 20-mm FSP (figure 3) based on the ballistic performance requirements of military specification MIL-DTL-32333. The AP M2 projectiles used were standard production, while the FSPs used were produced in accordance with MIL-DTL-46593B (MR) (*5*).

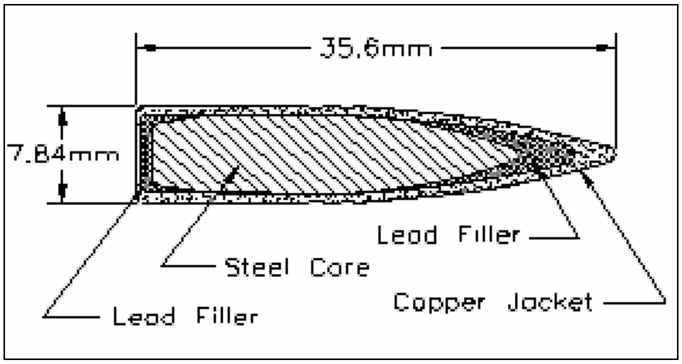

Figure 1. Diagram of 0.30-cal. AP M2 AP projectile.

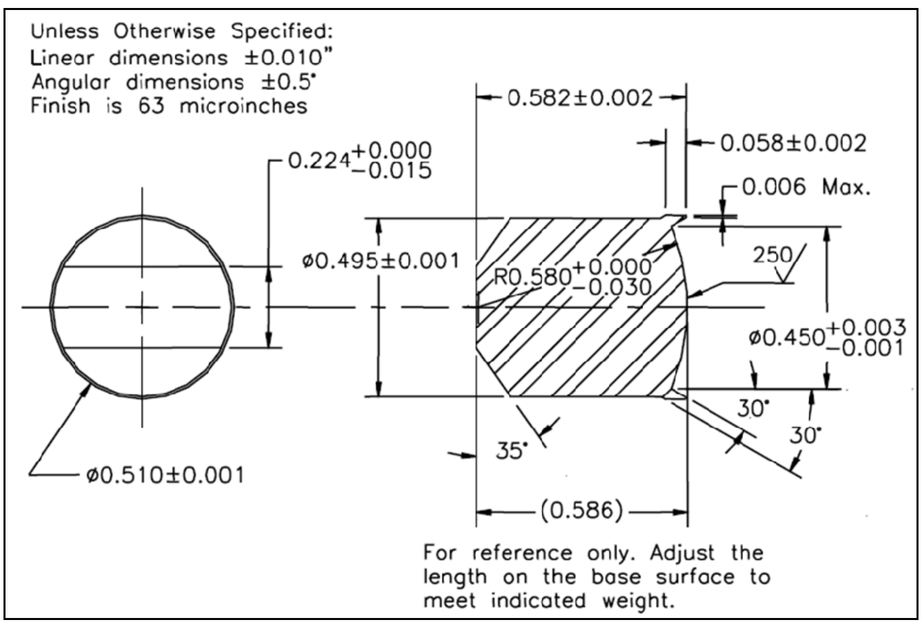

Figure 2. Diagram of 0.50-cal. FSP.

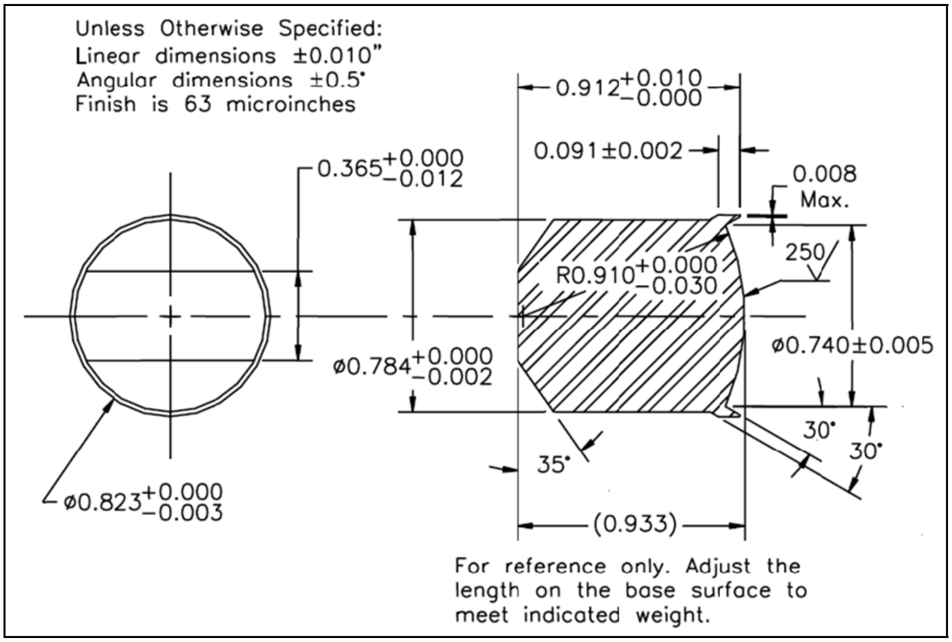

Figure 3. Diagram of 20-mm FSP.

4. Ballistic Evaluation

The V_{50} ballistic limit evaluation of each material was conducted by the Protection Division of ARL. The extruded plate of Mg E675-T5 was evaluated and compared to the performance of Mg baseline AZ31B-H24 and AA5083-H131 (*6*) on an equivalent weight (i.e., areal density) basis, as shown in figures 4–6. Linear interpolation (equation 1) was used to approximate data points for AZ31B and AA5083 using the respective minima from military specification MIL-DTL-32333 and MIL-DTL-46027K (*7*) for comparison to the Mg E675 ballistic limits (V_{50}'s). The tested ballistic limits for Mg E675 are shown in tables 3–5. The Mg E675 plate yielded a higher ballistic limit than Mg AZ31B and AA5083 for each projectile. However, as plate thickness increases, the difference in ballistic performance over AA5083 was significantly reduced. This trend was attributed to the lack of ductility in E675 compared to 5083, which reduced energy dissipation. Visual analysis of the Mg E675 plate showed massive shear cracking, which is a product of poor ductility. Pictures of the gross lateral cracking after ballistic impact for all projectiles are shown in appendices A, B, and C. Additionally, the lack of ductility resulted in large spall rings as the projectile perforated the Mg E675. The ballistic data and pictures for Mg E675 plate agree with the reported results from the TNO Defense, Security and Safety (The Netherlands) (*8*).

$$y = y_0 + (x - x_0)\frac{y_1 - y_0}{x_1 - x_0} , \tag{1}$$

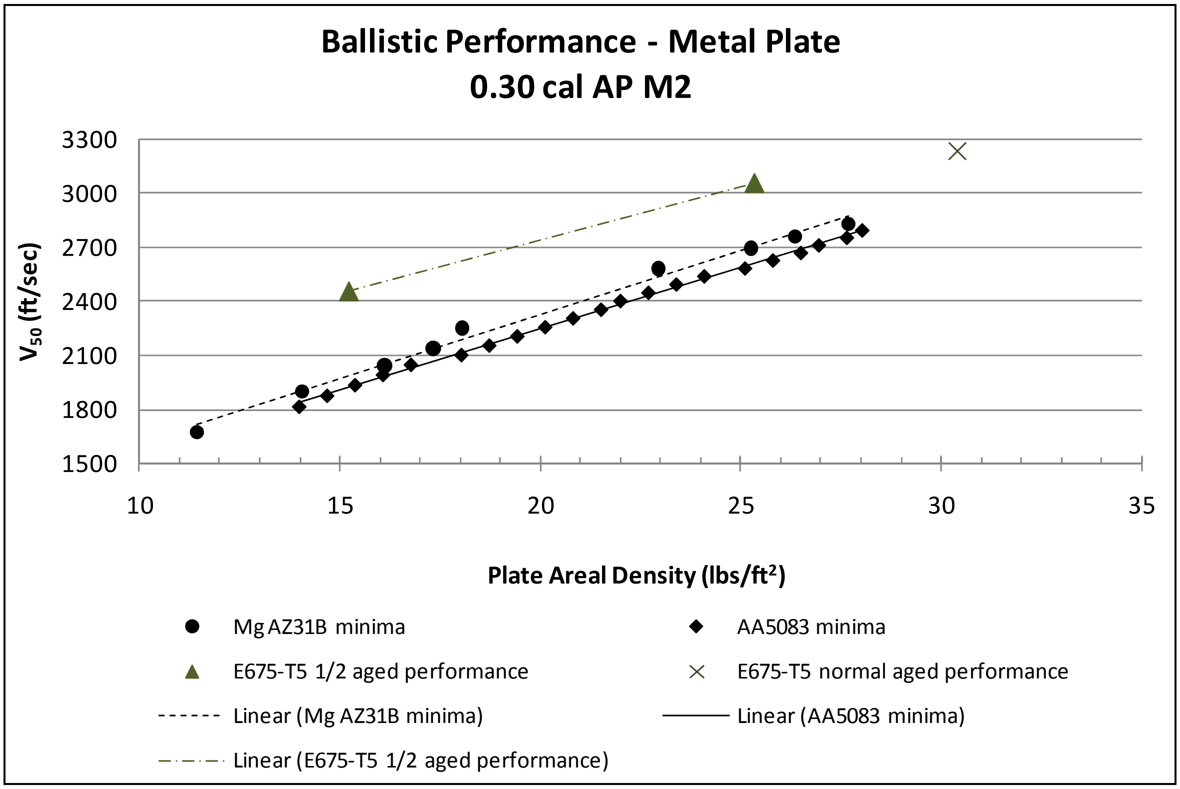

Figure 4. V_{50} ballistic limit of Mg alloy E675, Mg AZ31B, and AA5083 against 0.30-cal. AP M2.

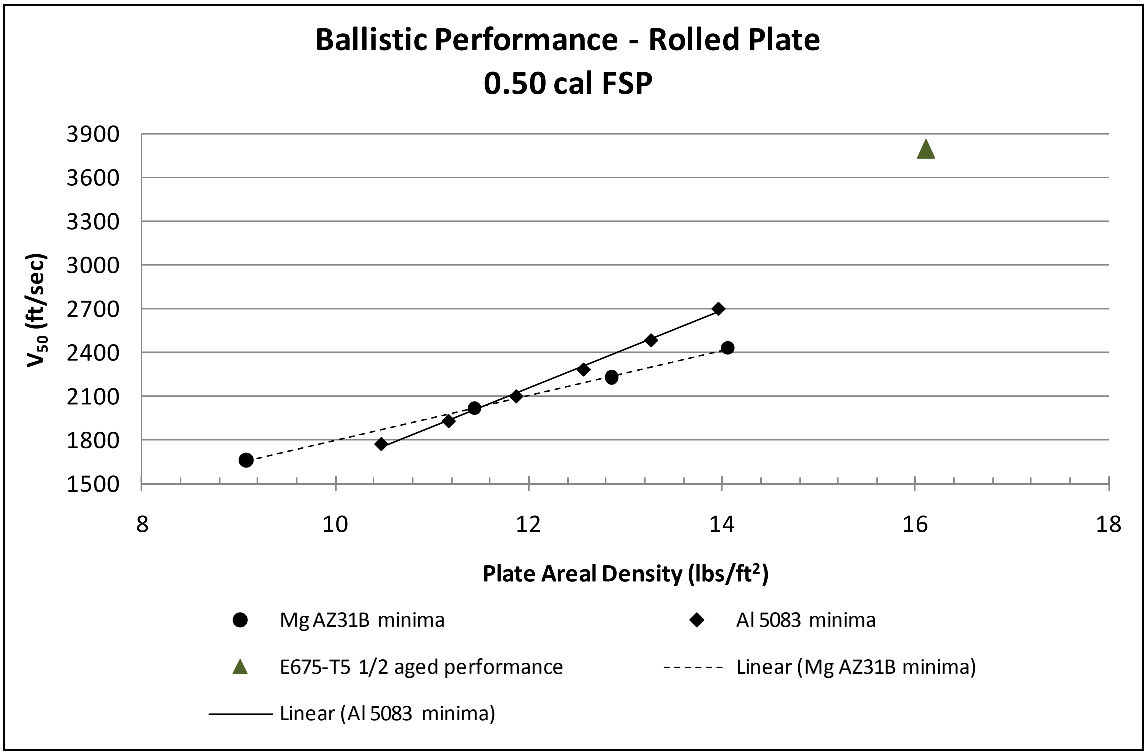

Figure 5. V_{50} ballistic limit of Mg alloy E675, Mg AZ31B, and AA5083 against 0.50-cal. FSP.

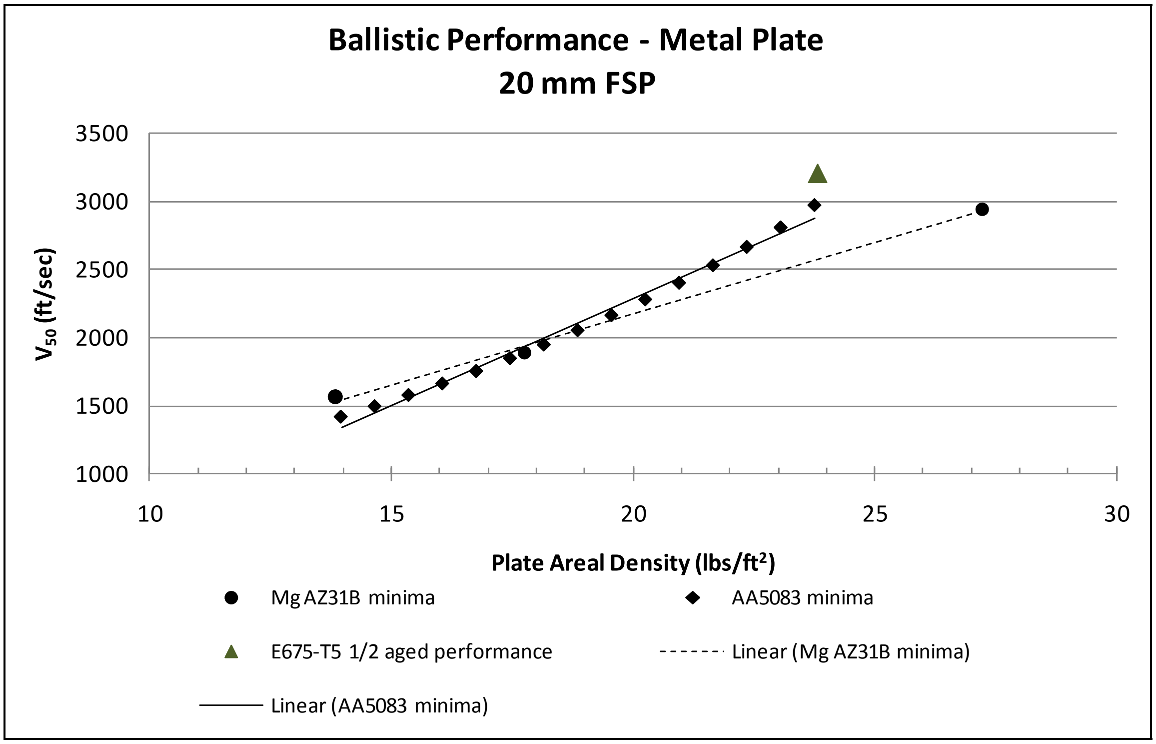

Figure 6. V_{50} ballistic limit of Mg alloy E675, Mg AZ31B, and AA5083 against 20-mm FSP.

Table 3. Comparison of the metal armor performance against the 0.30-cal. AP M2.

Areal Density (lb/ft^2)	Plate Thickness (in)	AZ31B (ft/s)	AA5083 (ft/s)	E675-T5 Half Aged (ft/s)	E675-T5 Normal Aged (ft/s)	Improvement Over AZ31B (%)	Improvement Over 5083Al (%)
15.21	1.5	1908	1924	2457	—	29	28
25.35	2.5	2702	2600	3054	—	13	17
30.42	3.0	2971	3053	—	>3231[a]	>9	>6

[a]Highest partial penetration.

Table 4. Comparison of the metal armor performance against the 0.50-cal. FSP.

Areal Density (lb/ft^2)	Plate Thickness (in)	AZ31B (ft/s)	AA5083 (ft/s)	E675-T5 Half Aged (ft/s)	Increased Improvement Over AZ31B (%)	Increased Improvement Over 5083Al (%)
16.11	1.59	2787	3369	3793	36	13

Table 5. Comparison of the metal armor performance against the 20-mm FSP.

Areal Density (lb/ft^2)	Plate Thickness (in)	AZ31B (ft/s)	AA5083 (ft/s)	E675-T5 Half Aged (ft/s)	Increased Improvement Over AZ31B (%)	Increased Improvement Over 5083Al (%)
23.82	2.35	2563	2989	3202	25	7

5. Corrosion Analysis

Corrosion analysis was conducted by the Materials Division of ARL. Visual and numerical corrosion assessments of E675 were initiated using accelerated corrosion experimental procedures GM 9540P (*9*) cyclic accelerated corrosion and ASTM B 117-90 (*10*) neutral salt fog (NSF), as described elsewhere (*11*). Under these methods, the E675 was evaluated vs. a variety of Mg-based alloys and commercially pure Mg (*12*). Aside from the commercially pure Mg, the E675 was the worst among the alloys for corrosion under both exposures. Its corrosion was characterized by dark staining and deep pitting that was produced in both environments but more severe under NSF. The relative corrosion rates among the Mg alloys and CP Mg under the accelerated corrosion exposures are plotted in figure 7. GM 9540P cyclic corrosion scans and NSF scans of the E675-T5 are displayed in figures 8 and 9. Finally, visual comparisons of the E675 to Mg alloy AZ31B (MIL-DTL-32333) and AA5083-H131 (MIL-DTL-46027K) (*7*) for both the GM cyclic exposure and the NSF appear in figures 10 and 11, respectively.

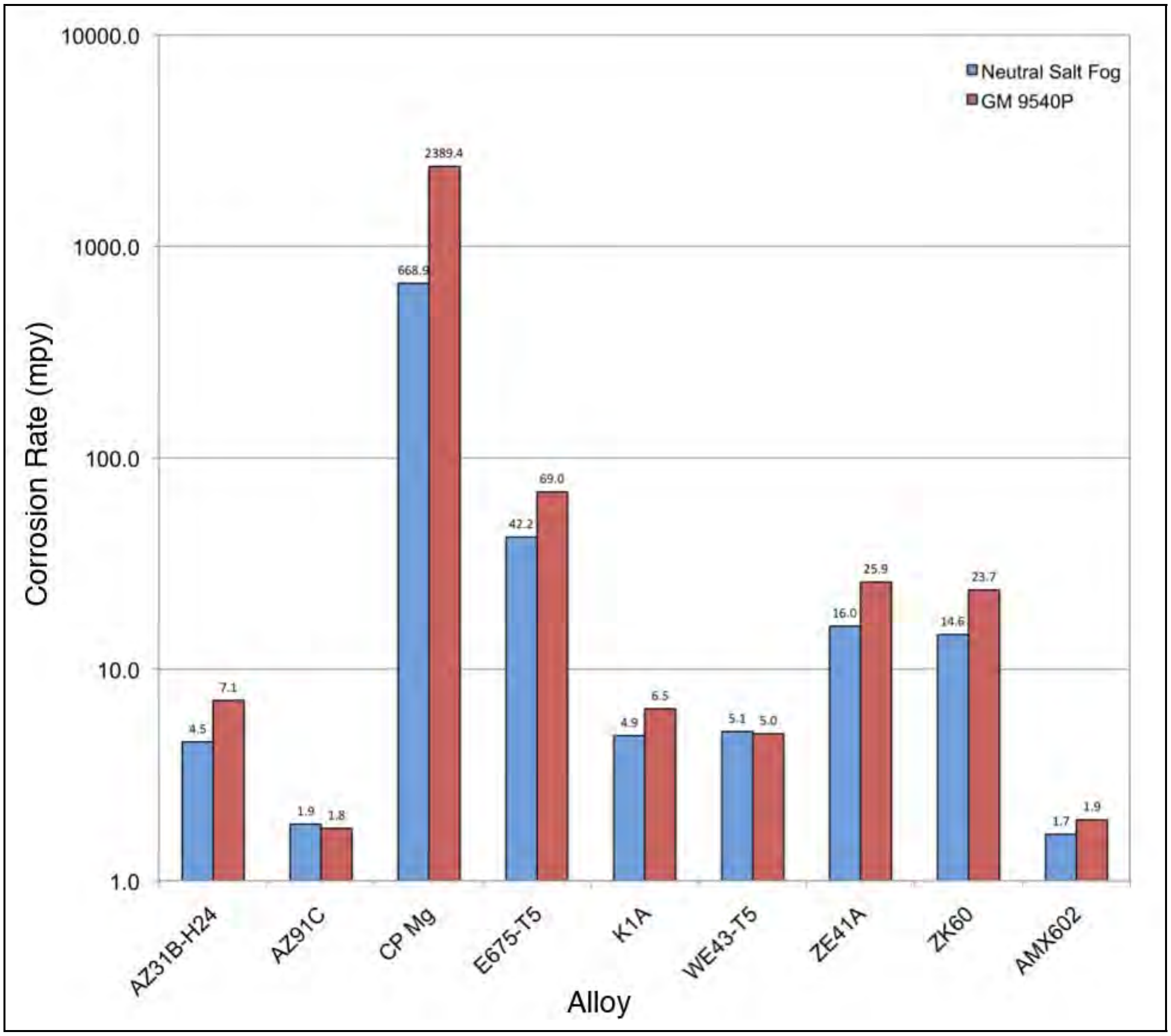

Figure 7. Corrosion rates in mils per year (mpy) based upon mass loss measurements after neutral salt fog (red) and GM 9540P cyclic corrosion exposures (blue).

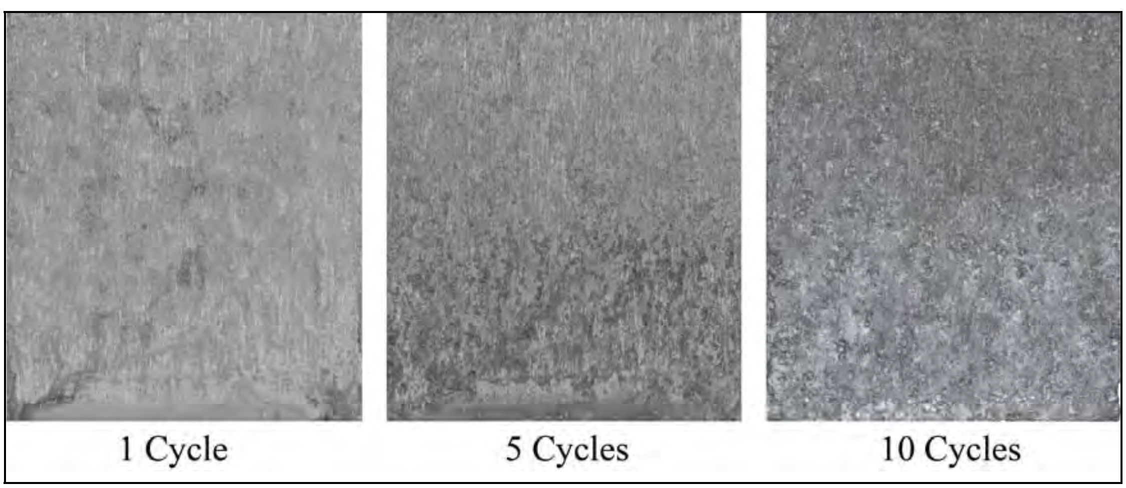

Figure 8. E675-T5 after GM 9540P cyclic corrosion.

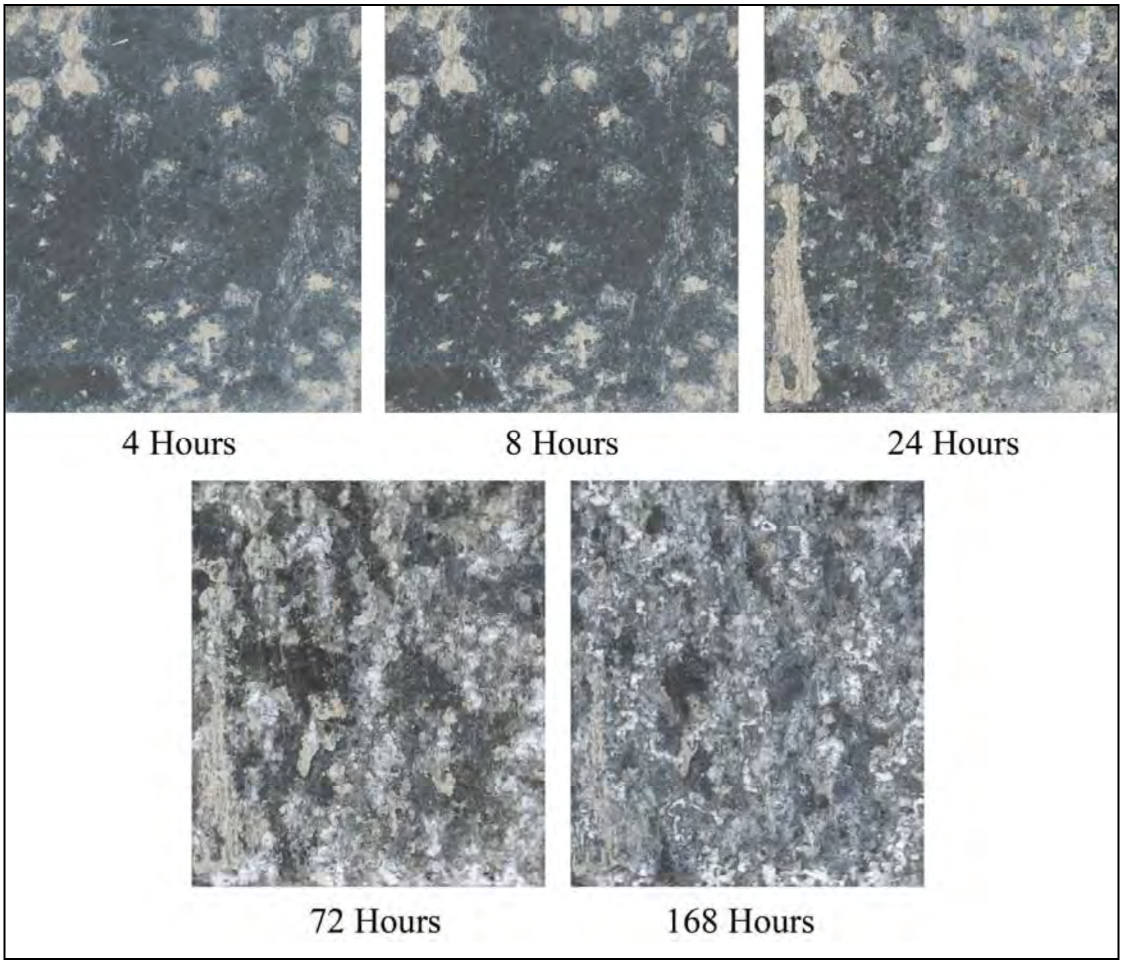

Figure 9. E675-T5 after neutral salt fog.

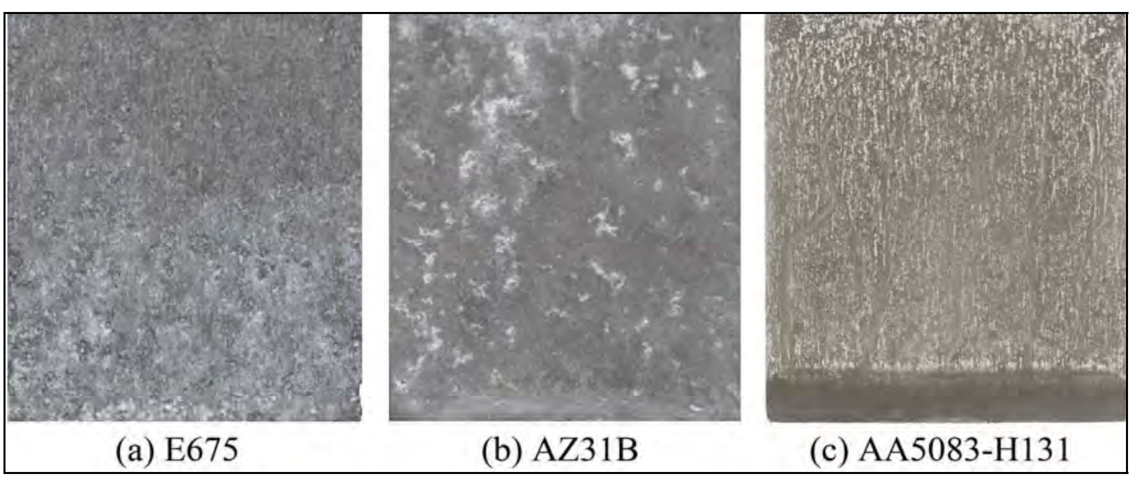

Figure 10. GM 9540P corrosion comparisons between armor plate alloys at 10 cycles.

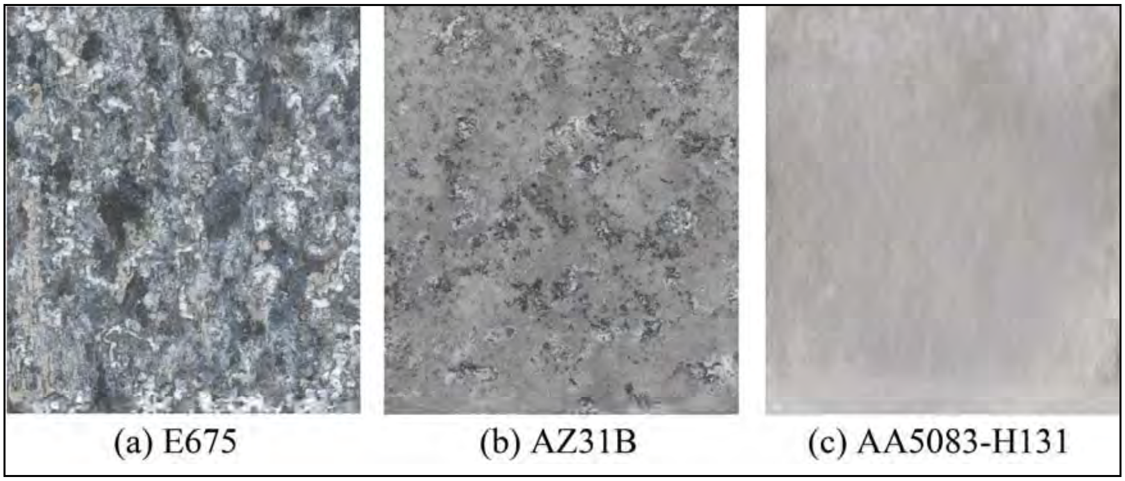

Figure 11. ASTM B 117 neutral salt fog comparisons between armor plate alloys at 168 hours.

6. Conclusion

Mg alloy E675 offers a higher ballistic protection by as much as 28% (depending on projectile) at equal weight for single impacts when compared to baseline Mg AZ31B and Al alloy 5083. The rare earths' elements (proprietary by Magnesium-Electron) in the chemical composition of Mg E675 increase the weight of the material. As thickness increases, the percent improvement in ballistic performance of Mg E675 over Mg AZ31B and AA5083 is significantly reduced. This trend is attributed to the lack of ductility in Mg E675 compared to AA5083, which reduced energy dissipation of the material. Additionally, the massive cracking through and across Mg E675 and extremely poor inherent corrosion resistance of the alloy will need to be addressed before it can be considered a robust solution for armor applications. The Mg E675 does not pass the corrosion resistance requirement specified in military specification MIL-DTL-32333. Lastly, the rare earths' elements in the chemical composition of Mg E675 will likely increase the cost of the material compared to Mg AZ31B and AA5083.

7. References

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6. Jones, T.; DeLorme, R. *Development of a Ballistic Specification for Magnesium Alloy AZ31B*; ARL-TR-4664; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, December 2008.
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10. ASTM B 117-90. Standard Method of Salt Spray (Fog) Testing. *Annu. Book ASTM Stand.* **1990**.
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Appendix A. Ballistic Test Data and Pictures, 0.30-cal. Armor-Piercing M2

This appendix appears in its original form, without editorial change.

Ballistic Data & Pictures
1.5" Magnesium E675-T5 Plate, ½ aged

Target:	**Magnesium E675-T5; 1/2 aged time**	18-Oct-07
Plate #:	DF 9240-675	EF106
Lot#:		
Thickness:	40.360mm (Plate #2: 1.588")	

Hardness:	131 BHN on 3000kg scale (Plate #2: 131)
Obliquity:	0°
Projectile:	.30-cal APM2

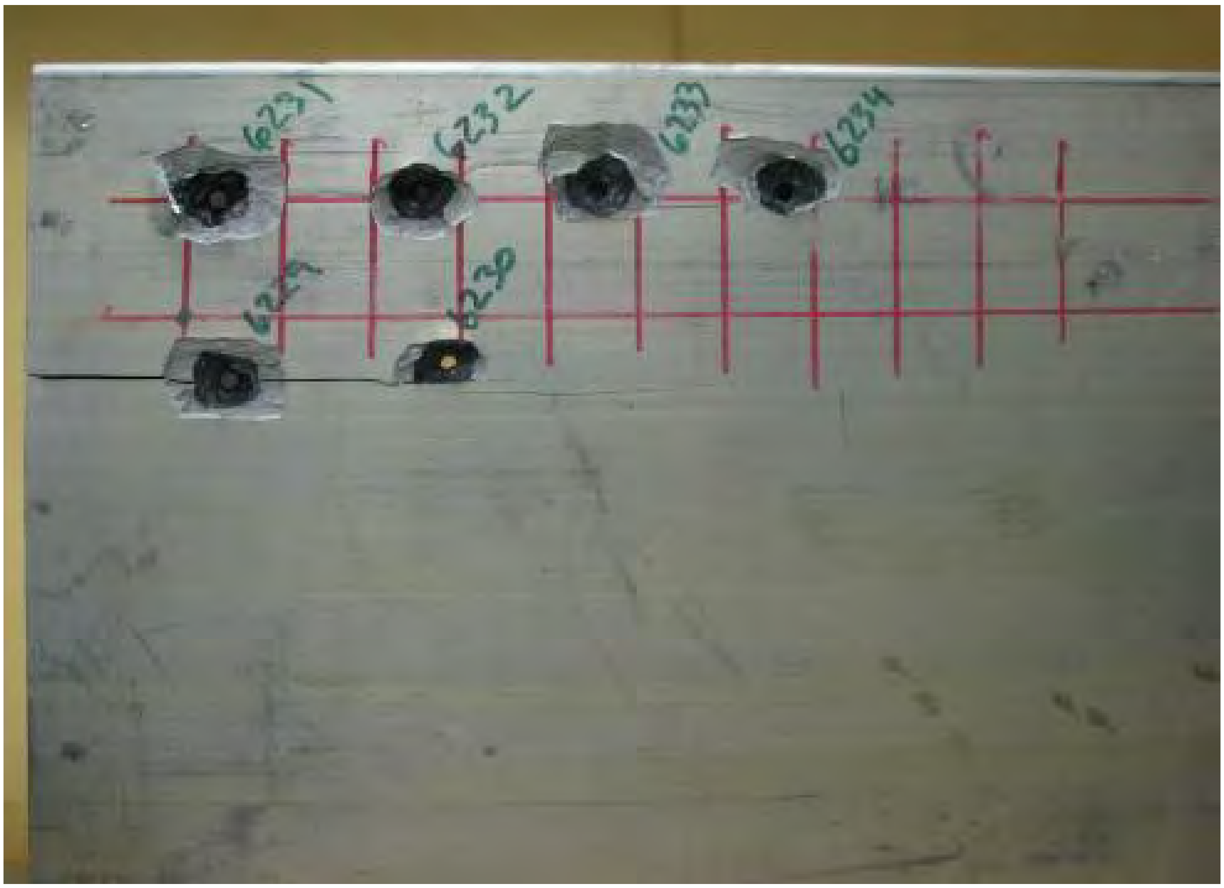
Setup: Mg-Air(6")-AL 2024(0.20")

V50:	749 m/s	**# shots:**	4
Std Dev:	7 m/s	**Spread:**	15 m/s
ZMR:	0		

Striking Velocity (m/s)	Striking Velocity (ft/s)	Pitch (deg)	Yaw (deg)	Result (PP/CP)	Comments	Shot #	
721	2366	--	--	PP	--	6229	Plate #2
757	**2483**	**--**	**--**	**CP**	--	6230	"
723	2372	--	--	PP	--	6231	"
742	**2435**	**--**	**--**	**PP**	--	6232	"
744	**2439**	**--**	**--**	**PP**	--	6233	"
754	**2472**	**--**	**--**	**CP**	--	6234	"

Pictures

(a) Entry



(b) Exit

Ballistic Data & Pictures
2.5" Magnesium E675-T5 Plate, ½ aged

Target:	**Magnesium E675-T5; 1/2 age time**	10/19/2007-10/22/2007
Plate #:	DF 9242-675	EF106
Lot#:		
Thickness:	59.919mm (2.359")	

Hardness: 131 BHN on 3000kg scale
Obliquity: 0°
Projectile: .30-cal APM2

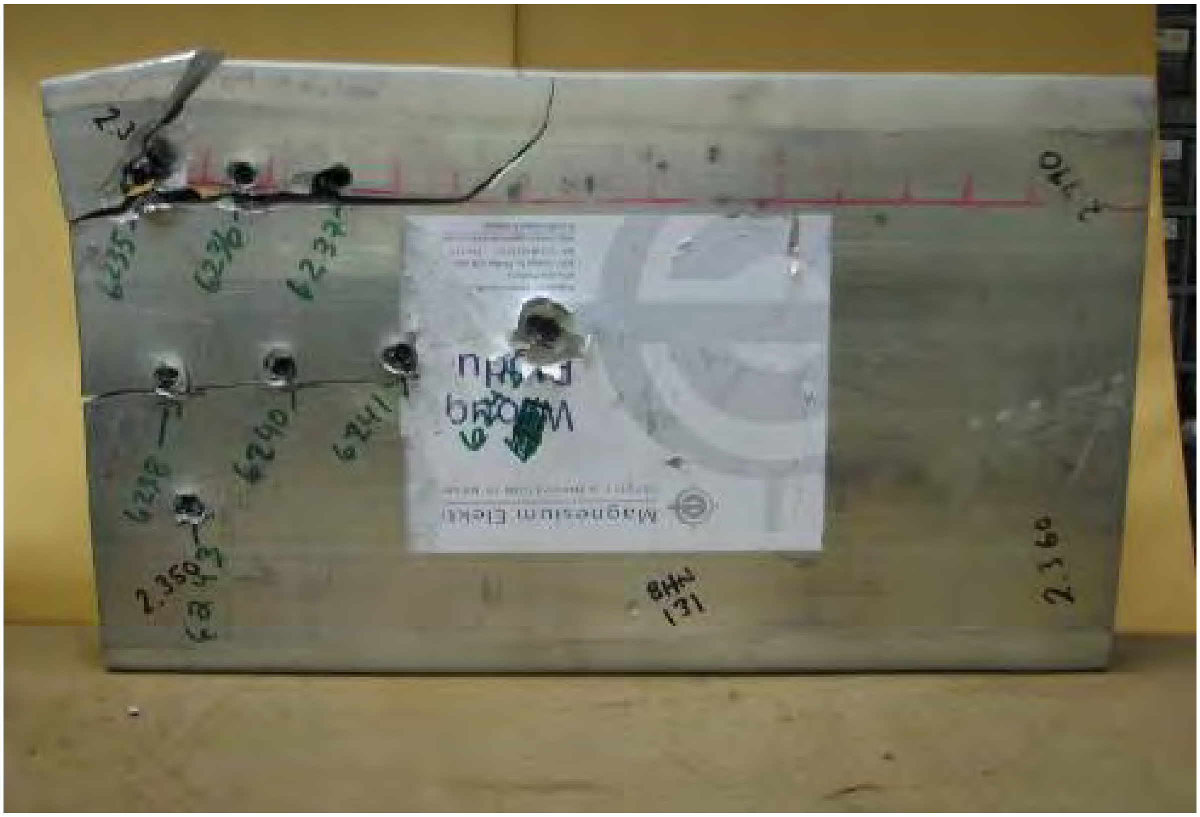
Setup: Mg-Air(6")-AL 2024(0.20")

V50:	931 m/s	**# shots:**	4
Std Dev:	7 m/s	**Spread:**	17 m/s
ZMR:	2		

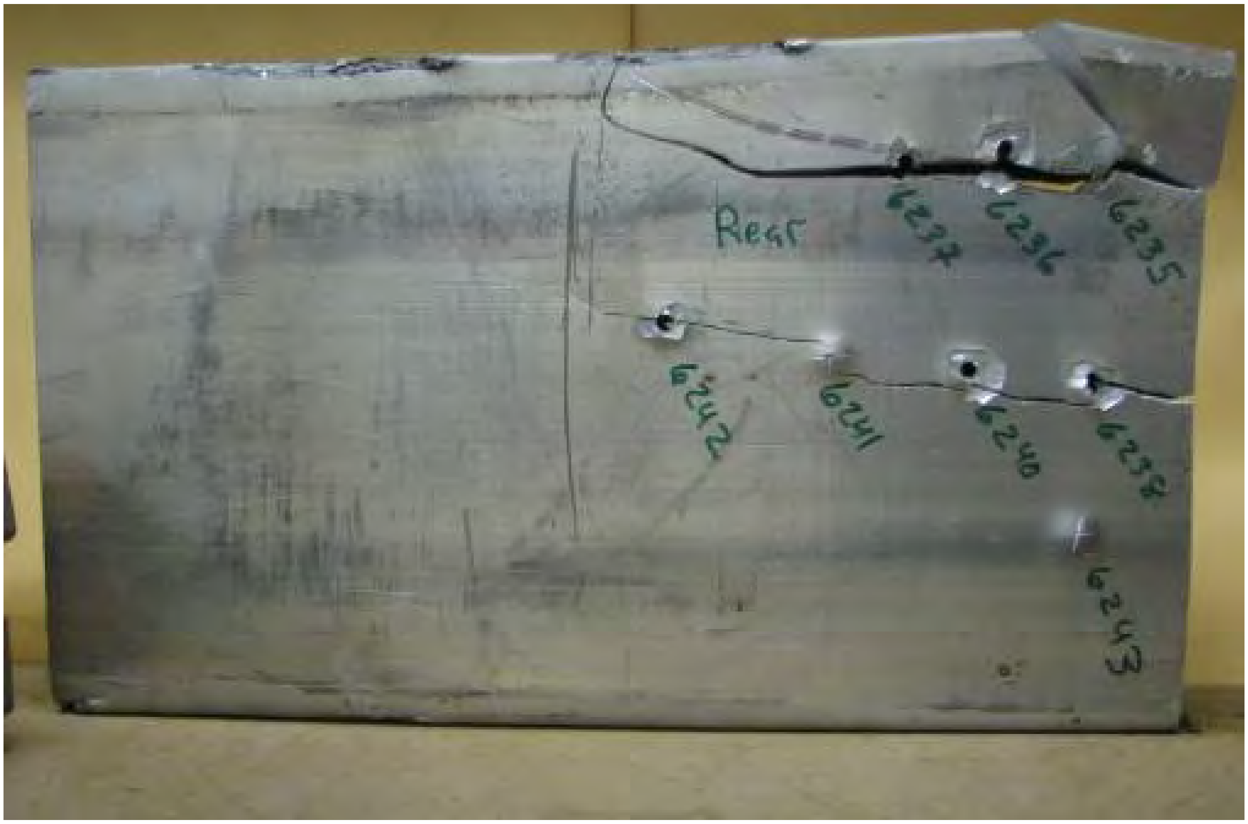
Striking Velocity (m/s)	**Striking Velocity (ft/s)**	**Pitch (deg)**	**Yaw (deg)**	**Result (PP/CP)**	**Comments**	**Shot #**
902	2957	--	--	PP	--	6235
961	3153	--	--	CP	--	6236
948	3111	--	--	CP	target corner broke off	6237
940	**3084**	**--**	**--**	**CP**	**--**	**6238**
941	3086	--	--	CP	--	6240
931	**3054**	**--**	**--**	**PP**	**--**	**6241**
929	**3048**	**--**	**--**	**CP**	**--**	**6242**
923	**3027**	**--**	**--**	**PP**	**--**	**6243**

Pictures

(a) Entry



(b) Exit



Ballistic Data & Pictures
1.5" Magnesium E675-T5 Plate, Full-age

Target:	**Magnesium E675-T5; full-age time**	**7-Nov-06**
Plate #:		**EF106**
Lot#:		
Thickness:	**31.596mm (2.964")**	

Hardness:	**128 BHN on 3000 scale**
Obliquity:	**0°**
Projectile:	**.30 cal APM2**

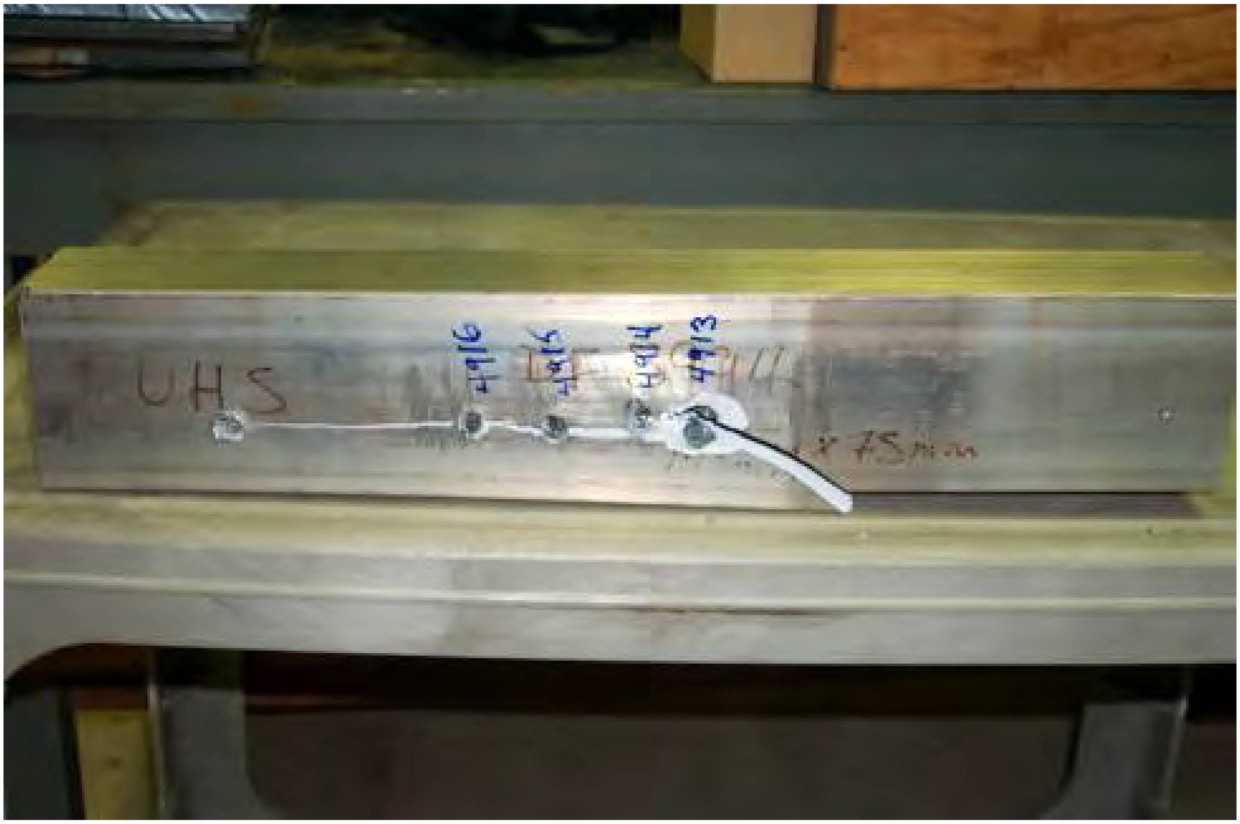
Setup: Mg-Air(6")-AL 2024(0.20")

V50:	934 m/s	**# shots:**	4
Std Dev:	79 m/s	**Spread:**	0 m/s
ZMR:	0		

Striking Velocity (m/s)	Striking Velocity (ft/s)	Pitch (deg)	Yaw (deg)	Result (PP/CP)	Used for V50	Comments	Shot #	
818	**2683**	**--**	**--**	**PP**	**Yes**	**No Bulge.**	**4913**	
869	**2851**	**--**	**--**	**PP**	**Yes**	**No Bulge.**	**4914**	
949	**3112**	**--**	**--**	**PP**	**Yes**	**No Bulge.**	**4915**	
984	**3228**	**--**	**--**	**PP**	**Yes**	**No Bulge. Large Cracking in plate.**	**4916**	**MAX LOAD**
985	**3231**	**--**	**--**	**PP**	**Yes**	**No Bulge. Large Crack.**	**4917**	**MAX LOAD**

Pictures

(a) Entry



(b) Exit

Appendix B. Ballistic Test Data and Pictures, E675-T5, 0.50-cal. Fragment Simulating Projectile

This appendix appears in its original form, without editorial change.

Ballistic Data & Pictures
1.5" Magnesium E675-T5 Plate, ½ aged time

Setup: Mg-Air(6")-AL 2024(0.20")

V50:	1156 m/s		**# shots:**	4
Std Dev:	6 m/s		**Spread:**	13 m/s
ZMR:	1 m/s			

Striking Velocity (m/s)	**Striking Velocity (ft/s)**	**Pitch (deg)**	**Yaw (deg)**	**Result (PP/CP)**	**Comments**	**Shot #**	
785	2573	--	--	PP	Slight Bulge.	5709	Plate #1
986	3233	--	--	PP	Slight Bulge.	5710	"
1128	3700	--	--	PP	Medium Bulge. Spall Forming.	5711	"
1203	3947	--	--	CP		5712	"
1158	**3798**	**--**	**--**	**PP**	**Large Bulge. Spall Forming.**	**5713**	"
1182	3877	--	--	CP		5714	"
1160	**3805**	**--**	**--**	**CP**		**5715**	"
1174	3850	--	--	CP		5716	"
1157	**3796**	**--**	**--**	**CP**		**5717**	"
1147	**3762**	**--**	**--**	**PP**		**5718**	Plate #2

Pictures

Plate 1

(a) Entry

Plate 1

(b) Exit

Pictures

Plate 2

(a) Entry

Plate 2

(b) Exit

Appendix C. Ballistic Test Data and Pictures, E675-T5, 20-mm Fragment Simulating Projectile

This appendix appears in its original form, without editorial change.

Ballistic Data & Pictures
2.5" Magnesium E675-T5 Plate, ½ aged time

Target: **Magnesium E675-T5; 1/2 age time** 24-Oct-07
Plate #: DF 9242-675 (Plate 1) EF108
Lot#:
Thickness: 59.666mm (2.349") (Avg. of P1: 2.359", P2: 2.346", P3: 2.343")

Hardness: 131 BHN on 3000kg scale
Obliquity: 0°
Projectile: .20-mm FSP

Setup: Mg-Air(6")-AL 2024(0.20")

V50:	976 m/s	**# shots:**	4
Std Dev:	8 m/s	**Spread:**	18 m/s
ZMR:	0 m/s		

Striking Velocity (m/s)	Striking Velocity (ft/s)	Pitch (deg)	Yaw (deg)	Result (PP/CP)	Comments	Shot #
1222	4009	--	--	CP	Plate 1	5757
1032	3389	--	--	CP	"	5758
943	3093	--	--	PP	Plate 2 - Dent in witness	5759
965	**3166**	**--**	**--**	**PP**	**Plate 2 - Dents in witness**	**5760**
1001	3283	--	--	CP	Plate 2	5761
985	3231	--	--	CP	"	5762
983	**3225**	**--**	**--**	**CP**	**Plate 3**	**5763**
977	**3204**	**--**	**--**	**PP**	**Plate 3 - Dents in witness**	**5764**
980	**3214**	**--**	**--**	**CP**	**Plate 3**	**5765**

Pictures

Plate 1

(a) Entry

Plate 1

(b) Exit

Plate 2

(b) Entry

Plate 2

Exit

Plate 3

(a) Entry

Plate 3

(B) Exit

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